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ASSESSING LOWER-SECONDARY SCHOOL STUDENTS' CRITICAL THINKING SKILLS IN PHOTOSYNTHESIS: A RASCH MODEL APPROACH

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Abstract. *The current study uses the Rasch Model to measure lower-secondary school students' critical thinking skills on photosynthesis topics. Critical thinking skills are considered essential in science education, but few valid and practical measurement instruments remain. The current study fills the gap by adapting the instrument from the Watson-Glaser Critical Thinking Appraisal. A quantitative approach with a survey design was used in the study, involving 467 lower-secondary school students in Klaten, Central Java, Indonesia. Data were analyzed using the Rasch Model to evaluate each item's reliability, validity, level of difficulty, and discrimination ability. The results suggest that the instrument has good validity and reliability, with the inference subscale being the most difficult, while evaluation is the easiest for students to master. The findings provide insights for educators in designing more effective teaching strategies to develop critical thinking skills. The study implies that a valid measurement instrument is obtained and offers new insights into the profile of students' critical thinking skills in science learning to support more effective science teaching in secondary schools, especially on photosynthesis.*

Keywords: *critical thinking, educational evaluation, photosynthesis topic, Rasch model, science education*

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Introduction

Critical thinking skills are essential capabilities students must possess because they help students analyze information, make inferences, and make evidence-based decisions. Developing critical thinking skills among lower-secondary school students is essential in 21st-century education (Affandy et al., 2024; Raslan & Forawi, 2024), especially in science subjects such as photosynthesis. Critical thinking skills are an integral part of the scientific process, involving observation, analysis, interpretation, and data evaluation (Han & Abdrahim, 2023). Therefore, developing critical thinking skills in science students is relevant and essential to becoming independent and innovative problem solvers. Previous studies have concluded that students with critical thinking skills can identify problems, evaluate information, and make appropriate decisions compared to students who are less trained (Golumbic et al., 2022; Sithole, 2023). Critical thinking skills enhance students' ability to solve complex problems and stimulate their curiosity towards natural phenomena (Falloon et al., 2022).

Critical thinking skills are relevant in the context of photosynthesis learning in lower-secondary school, especially in the Indonesian education curriculum. Developing critical thinking skills in students in learning photosynthesis enhances the quality of science learning by encouraging students to understand scientific concepts more deeply and critically (Teresa & Fields, 2023). Various studies have suggested that students trained in critical thinking skills are more capable of analyzing and evaluating scientific processes (Han & Abdrahim, 2023), such as the chemical reactions involved in photosynthesis, rather than simply memorizing information (Yeung et al., 2023). The education curriculum in Indonesia emphasizes conceptual understanding and application of knowledge rather than rote memorization, so critical thinking skills are relevant to encourage students to explore scientific questions (Anggraeni et al., 2023). Through implementing the National Curriculum (in Indonesian "*Kurikulum Merdeka*"), education policy in Indonesia emphasizes strengthening critical, creative, and collaborative characters and skills.

Previous research has indicated a gap in measuring critical thinking skills in science education (Baran et al., 2021; Clements & Joswick, 2018; Teresa & Fields, 2023), especially on photosynthesis material, where existing instruments often fail to accurately assess the various dimensions of critical thinking, such

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as inference, deduction, and evaluation. The measurement of critical thinking skills in the context of photosynthesis has not been fully explored, thus requiring further research to ensure appropriate and relevant instruments (Chou et al., 2019). The results of previous studies have suggested that many critical thinking skills measurement instruments used in schools are not explicitly designed to measure these skills in the context of science (Amin et al., 2017; García-Carmona, 2023), let alone the complex material of photosynthesis. Critical thinking skills are domain-specific, meaning that students need approaches and measurement instruments based on the characteristics of science materials to obtain valid and reliable measurement results. Measuring critical thinking skills in science requires a content-based approach (Marthaliakirana et al., 2022; Wang et al., 2023), where measurement instruments are adapted to the structure and concepts in the field of study, such as photosynthesis in biology. Measurement of critical thinking skills, in general, has been widely researched and applied in various disciplines (Chou et al., 2019). Nevertheless, essential instruments of thinking, in general, can provide a general overview of students' critical thinking skills (García-Carmona, 2023), but obtaining a more detailed understanding in the context of science (Marthaliakirana et al., 2022), such as photosynthesis, is essential so that the resulting measurements truly reflect students' ability to apply critical thinking skills to the material being studied.

The theory of measuring critical thinking skills in the context of science learning, especially on photosynthesis material in lower-secondary school, is the Watson-Glaser Critical Thinking Appraisal, which emphasizes the levels of inference, assumption, deduction, interpretation, and evaluation (Ennis, 1958). The theory proposed in the Watson-Glaser Critical Thinking Appraisal is relevant in measuring students' critical thinking skills because it focuses on cognitive abilities in understanding scientific concepts such as photosynthesis (Giri & Paily, 2020). The results of various studies have suggested that when students are trained in inference, assumption, deduction, interpretation, and evaluation, they can understand science material more deeply and critically (Bilandzic & Blessing, 2022). Critical thinking skills involve the ability to remember or understand concepts and higher cognitive processes such as identifying cause-and-effect relationships, testing hypotheses, and evaluating evidence (Culver et al., 2022). Therefore, critical thinking skills contribute to the mastery of science material, which involves experimentation, observation, and inference.

The Rasch model has a role in measuring critical thinking skills because it provides a more objective and reliable approach to assessing student ability. The Rasch model enables accurate and consistent measurement of essential thinking skills, considering the difficulty level of each item and individual student abilities (Linacre, 2011; Wang & Ho, 2024). Results from various studies have indicated that using the Rasch model in educational measurement produces more valid and reliable student ability estimates than traditional approaches because the Rasch model separates student ability from item characteristics (Cascella et al., 2020; Huelmann et al., 2020; Wind, 2019). The Rasch model is based on probabilistic theory, which assumes that the higher a student's critical thinking ability is, the more likely they are to answer complex questions correctly (Bond, 2015). Meanwhile, students with lower abilities have a greater chance of answering easier items correctly, making the measurement fairer and more accurate (Affandy et al., 2021; Laliyo et al., 2022).

Notwithstanding that the Rasch model has been widely used for various types of measurement in education, its use to measure the critical thinking skills subscale is still limited, especially in the context of science learning. Previous studies that have used the Rasch Model have focused on measuring general competencies and do not precisely measure the dimensions of critical thinking in the context of specific materials (Cascella et al., 2020; Collado et al., 2015), such as photosynthesis. Critical thinking skills consist of several different subscales (Ennis, 1958), thus requiring measurement instruments designed to measure each ability separately (Affandy et al., 2021; Laliyo et al., 2022). The Rasch Model, with its ability to precisely measure item difficulty and individual ability, has great potential to measure each subscale of critical thinking skills accurately (Linacre, 2011). The results of previous studies have suggested that the Rasch Model provides more precise results in measuring cognitive abilities and complex thinking skills because it analyzes the reliability and validity of the instrument in more depth (Cascella et al., 2020; Huelmann et al., 2020; Wind, 2019).

Measuring critical thinking skills in photosynthesis material is essential to ensure that students not only understand concepts superficially but can also infer, test assumptions, deduce, interpret, and evaluate scientific knowledge in a broader context (Ennis, 1958). The PISA report has indicated students' low critical thinking skills in Indonesia (PISA, 2023), where many students still rely on memorization and are less trained in exploring scientific concepts in depth (Fensham & Bellocchi, 2013). Photosynthesis is an essential concept in the lower-secondary school science curriculum that requires theoretical understanding and analytical ability to relate the process to environmental phenomena and daily life (Layer et al., 2010). Critical thinking skills are essential in this case, as students must be able to evaluate the impact of environmental changes on photosynthesis and its ecological implications (Marthaliakirana et al., 2022; Wang et al., 2023). National and international education policies emphasize the importance of critical thinking skills as part of students' competencies to global challenges.

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Research Aim and Research Questions

The research aimed to identify and measure the critical thinking skills of lower-secondary school students in the context of science learning, especially on photosynthesis. The specific goal of this study was to measure the critical thinking skills of lower-secondary school students on photosynthesis material. It involves complex concepts that require students to apply reasoning and critical thinking to understand mechanisms, processes, and their implications. Moreover, photosynthesis is a topic where students typically encounter challenges in grasping abstract concepts, making it an ideal context to assess and develop critical thinking skills. Adopting the Rasch Model as a measurement approach provided deeper insights into the accuracy and reliability of evaluating students' critical thinking skills in science learning. The research questions addressed through the study included: (1) How was the reliability and validity of the critical thinking skills measurement instrument using the Rasch Model on photosynthesis material? (2) What was the level of difficulty and discrimination ability of each critical thinking skill item in the measurement using the Rasch Model on photosynthesis material? and (3) Were there subscale differences in students' critical thinking skills (inference, assumption, deduction, interpretation, and evaluation)?

Research Methodology

General Background

The research used a quantitative approach, applying the Rasch model to analyze students' critical thinking skills. The research design was evaluative, with data collected from lower-secondary school students in Klaten, Central Java, Indonesia, in the 2023 school year. The research focused on measuring specific critical thinking skills—such as inference, assumption, deduction, interpretation, and evaluation—using a test adapted from the Watson-Glaser Critical Thinking Appraisal (Ennis, 1958). The Rasch model was chosen as the primary instrument testing tool due to its objectivity in providing detailed item analysis and estimation of student ability, thus enabling a deeper understanding of how students critically process information in learning complex science topics such as photosynthesis. The study also considered contextual factors such as the educational curriculum, thus providing a comprehensive background for the study.

Research Design

The study used a descriptive quantitative design with a survey approach (Creswell, 2012), which aimed to describe the factual conditions of students' critical thinking skills based on the results of test measurements. The study did not attempt to manipulate variables but only measured and analyzed students' critical thinking skills naturally. The study was conducted from May to June 2023 in lower-secondary schools in the Klaten Region, Central Java, Indonesia, and involved 467 randomly selected grade VIII students. The topic tested was specific to photosynthesis according to the prevailing science curriculum.

Participants

The total population of students who were the subject of the study was 729 lower-secondary students, who were selected based on criteria relevant to the purpose of the study. The selection of participants was made using the random sampling method, where students were randomly assigned to ensure that each individual in the population had an equal chance of being involved in the study. A sample size of 467 students was drawn from the total population of 729 lower-secondary students. The random sampling approach was chosen to minimize bias in selecting participants so that the study results would be more representative and could be generalized to the entire population. Inclusion criteria to determine student participation included (1) having completed the photosynthesis material and (2) students with at least 80% attendance in related lessons. Exclusion criteria included students with an attendance record of less than 80%, students who had not studied the material under study, and students with special needs requiring intervention. The inclusion and exclusion criteria were used to control variables that could interfere with the analysis results.

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Table 1
Characteristics of Survey Respondents

Characteristic	Sub-characteristic	*N*	%
Gender	Male	237	50.75
	Female	230	49.25
	Total	467	100
Age	13 Years	260	55.67
	14 Years	207	44.33
Academic Achievement	< 70	152	32.55
	70-85	188	40.26
	85	127	27.19
School location	Urban areas	160	34.26
	Rural areas	160	34.26
	Frontier regions	147	31.48

Participants in the study included 467 lower-secondary students with various demographic characteristics (see Table 1). The students' gender was almost evenly distributed, with 237 male students (50.75%) and 230 female students (49.25%). The participants were between 13 and 14 years old, with 260 students aged 13 (55.67%) and 207 students aged 14 (44.33%). Regarding academic achievement, the participants were divided into three groups: 152 students with academic scores below 70 (32.55%), 188 students with scores between 70-85 (40.26%), and 127 students who had academic achievement above 85 (27.19%). The students came from various school locations, with 160 students (34.26%) attending schools in urban areas, 160 students (34.26%) in rural areas, and 147 students (31.48%) coming from border areas. Measures to ensure clarity and transparency in the study included: (1) all participants were given an identification code, rather than using personal data such as names; (2) participation in the study was entirely voluntary, including the right to withdraw at any time without facing negative consequences; and (3) no incentives were offered to coerce participation, so student involvement was entirely voluntary and free from external pressure.

Data Collection

Data was collected using a paper test instrument and was supervised by the researcher and teacher to avoid intervention from other parties and ensure that each student gave an honest and independent response. The time allowed to complete the instrument was 45 minutes. Prior to the start of the session, the researcher gave brief instructions on the procedure for completing the instrument, which took about 5-10 minutes. The 45-minute duration was chosen to balance the effectiveness of data collection, participants' comfort, and to avoid fatigue that could affect the quality of students' responses. Data were collected in one session to minimize possible bias arising from external conditions.

Instruments Critical Thinking in Photosynthesis

The instrument to measure critical thinking skills in photosynthesis was adapted from the Watson-Glaser Critical Thinking Test. The development of the instrument began with a review of the components measured by Watson-Glaser, such as the ability to conclude, recognize assumptions, and evaluate arguments and interpretations (Ennis, 1958). These components were then adapted to be relevant to the concepts in photosynthesis. For example, questions were developed to assess the ability to analyze photosynthesis experimental data, evaluate hypotheses related to factors that affect the photosynthesis process, or draw conclusions based on scientific observations. Modifications were made so that the instrument remained valid in the context of biology learning, especially the topic of photosynthesis, while still maintaining the structure and objectives of measuring critical thinking skills as in the Watson-Glaser instrument.

The critical thinking skills measurement instrument in the context of photosynthesis consists of 12 items

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designed to measure five sub-skills. Inference is measured by three items that assess students' ability to conclude the data or information presented, such as the results of photosynthesis experiments. Assumption is represented by two items that evaluate students' ability to recognize hidden or implicit assumptions in scientific statements or arguments related to photosynthesis. Deduction is measured by three items that test how students use general principles of photosynthesis to draw logical conclusions from more specific situations. Interpretation is also measured by three items, where students are asked to interpret data or visual information, such as graphs or diagrams depicting the photosynthesis process. Evaluation is represented by one item that focuses on students' ability to evaluate scientific evidence related to claims about photosynthesis. An example of an evaluation item is presented in Figure 1.

Before analysis using the Rasch Model, instrument validity testing was conducted to ensure the instrument was valid and reliable in measuring critical thinking skills related to photosynthesis. Content validity was tested through expert judgment, where experts in biology education and educational measurement were asked to assess whether the items in the instrument reflected the critical thinking sub-skills to be measured. Experts also checked whether the items were relevant to the concept of photosynthesis and appropriate for students' level of understanding.

Figure 1

Example of CT Items on The Evaluation Subscale

Statement: A study from the journal Plose One, dated October 3, 2018, claims that we can hear the sound of photosynthesis from red algae when diving into the seafloor. The sound of photosynthesis sounds "ping". Although red algae are in the water, the photosynthesis process is the same as that of land plants. Sunlight shines into the water, converting carbon dioxide and water molecules into sugar and oxygen.

	Substantial reasoning
	The argument is relatively weak

Statistical Analysis

The unidimensionality of the instrument was tested to examine the assumption of unidimensionality required in applying the Rasch Model. Unidimensionality testing used Principal Component Analysis (PCA) to ensure that the instrument measured only one construct of students' critical thinking skills on photosynthesis material (Field, 2024). Data were analyzed using the Rasch model, part of item response theory, to examine the reliability and validity of the instrument and the characteristics of each item (Linacre, 2011). The Rasch Model parameters include Infit and Outfit Mean Square (MNSQ) values, which are used to evaluate whether each item fits the model's expectations and to identify items that are too difficult or too easy for participants (Adams et al., 2018).

Moreover, the Rasch Model is used to measure the instrument's reliability through the calculation of Person and Item Reliability and the Person-Item Separation Index, which indicates how well the instrument differentiates the level of critical thinking ability among students (Linacre, 2011; Nielsen et al., 2017). Infit and Outfit MNSQ values that fall within the range of 0.5 to 1.5 indicate that the item fits the model and measures what is expected (Linacre, 2011). Data analysis to test for differences between critical thinking sub-skills was based on data from the Rasch Model. First, a comparison was made of the percentage of correct answers in each sub-skill to see if there were differences in success rates between the sub-skills. Furthermore, item difficulty was compared for each sub-skill to evaluate whether item difficulty varied significantly. Standard errors were also analyzed to assess the precision of each sub-skill's estimated difficulty and to compare the measurement uncertainty level. Moreover, Infit and Outfit MNSQ statistics were analyzed for each sub-skill to check the fit of the Rasch model to each item, which provides insight into whether any sub-skills display different response patterns.

Research Results

Unidimensionality

The Kaiser-Meyer-Olkin (KMO) results and Bartlett's Test of Sphericity for the critical thinking skills instrument on photosynthesis material produced a KMO value of .791. The KMO value exceeded the recommended minimum

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threshold (.6), indicating that the data sample was sufficient for factor analysis (Field, 2024). Moreover, Bartlett's test proved significant with a chi-square value of 2054.07 (df = 66, p < .0001), which means that the correlation between items in the instrument was sufficient for factor analysis (Field, 2024). The total variance explained analysis revealed one main component with an eigenvalue above one, which explains 86.931% of the total variance. The assumptions of unidimensionality were met by having one dominant factor that explains most of the variance, indicating that the items in the instrument measure one construct.

Validity and reliability of the CT on Photosynthesis Topic

The critical thinking skills instrument on photosynthesis material had favorable characteristics based on the validity test results (see Table 2). The mean measure value for respondents was .49 logit (SD = 0.76), indicating that the average ability of test takers was slightly above the average difficulty level of the item (.001 logit; SD = 0.76). The Infit MNSQ and Outfit MNSQ values for the items ranged from .82 to 1.11 and .72 to 1.18, respectively, which are all within the acceptable range according to Boone (2014), generally .5 to 1.5. This indicates that none of the items were too easy or too difficult for the participants, and the items performed well in measuring critical thinking skills. However, there were some outliers in the Outfit MNSQ values for respondents, with the maximum value reaching 4.32, indicating that some respondents had inconsistent answer patterns or did not fit the predicted model.

Table 2
Validity and Reliability Test Results of Test Instruments

Parameter	Person (n = 467)			Item (n = 12)		
	Measure (logit)	Infit MNSQ (logit)	Outfit MNSQ (logit)	Measure (logit)	Infit MNSQ (logit)	Outfit MNSQ (logit)
M	0.49	1.00	1.01	0.00	1.00	1.01
SD	0.76	0.22	0.34	0.76	0.09	0.14
Max	2.65	1.71	4.32	1.26	1.11	1.18
Min	-2.60	0.55	0.38	-0.86	0.82	0.72
Reliability	.86			.95		

The reliability coefficient analysis at the person (.86) and item (.95) levels resulted in high values. Item reliability is higher than person reliability, indicating that the critical thinking skills instrument has a good level of consistency in terms of items, but there were some variations or inconsistencies in participants' responses. The variation in differences in reliability values occurred due to differences in individual abilities in responding to items, which caused the reliability at the person level to be slightly lower.

Item Difficulty of the CT on Photosynthesis Topic

The results of testing the level of difficulty of the items (Table 3) show that the level of difficulty of the items ranges from -0.86 logits (easiest) to 1.36 logits (most difficult), with the item that has the lowest level of difficulty being Item 6 and the highest being Item 3. The results of testing the items' difficulty level were in the moderate range and had a fairly excellent and varied distribution of item difficulty. Items with lower difficulty levels, such as Items 4, 5, 6, 9, 10, and 12, had a relatively high percentage of correct answers (between 66.81% and 77.09%), which indicates that these items are more accessible for students. However, items with higher difficulty, such as Items 2 and 3, had a lower percentage of correct answers (around 31.69% to 32.33%), which indicates that these items are relatively difficult for students.

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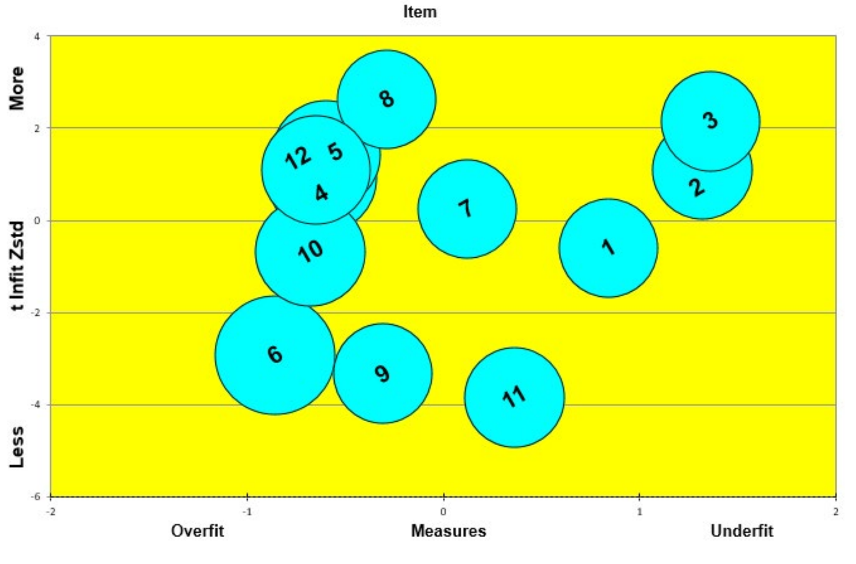
Table 3
Item Difficulty of the CT on Photosynthesis Topic

Item	Correct answer (%)	Item Difficulty (logit)	Standard error (logit)	Infit MNSQ (logit)	Outfit MNSQ (logit)	Point measure corr (logit)
Item 1	42.40	0.84	0.10	0.98	1.00	0.49
Item 2	32.33	1.32	0.10	1.05	1.15	0.54
Item 3	31.69	1.36	0.10	1.09	1.14	0.48
Item 4	73.02	-0.62	0.11	1.05	1.04	0.55
Item 5	72.81	-0.60	0.11	1.07	1.08	0.51
Item 6	77.09	-0.86	0.12	0.83	0.72	0.52
Item 7	58.24	0.12	0.10	1.01	1.02	0.52
Item 8	66.81	-0.29	0.10	1.11	1.18	0.56
Item 9	67.24	-0.31	0.10	0.87	0.81	0.50
Item 10	74.09	-0.68	0.11	0.96	0.94	0.75
Item 11	53.10	0.36	0.10	0.89	0.87	0.67
Item 12	73.66	-0.65	0.11	1.06	1.13	0.51

The results of testing the difficulty level of the items showed that none of the items were either too difficult or too easy in the extreme (see Figure 2). Although Item 6 had the lowest difficulty level (-0.86 logit), with 77.09% of students answering correctly, and Item 3 had the highest difficulty level (1.36 logit), with only 31.69% of students answering correctly, these two items were still within the acceptable difficulty limit for measuring critical thinking skills. The measures value (see Figure 2) reflects the difficulty level of each item on a logit scale. Items with positive measure values, such as item 2 (1.32 logit) and item 3 (1.36 logit), are classified as more difficult items for students, while items with negative measure values, such as item 10 (-0.31 logit) and item 6 (-0.86 logit), are considered more accessible by students. The Infit Zstd value illustrates how well the item fits the Rasch model (see Figure 2). The expected value is around 0, with an acceptable range generally between -2 to +2. Items such as item 6 (-2.92) and item 11 (-3.85) had more extreme negative Infit Zstd values, meaning that student responses to these items were consistent with those predicted by the model.

Figure 2
Bubble Chart of The CT Item Difficulty



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The point measure correlation values for each item ranged from 0.48 to 0.75, indicating that the items generally had a positive correlation with student ability. The point measure correlation value indicates that the higher the score on an item, the more likely it is that the student has better critical thinking skills. Higher point measure correlation values, as seen in Item 10 (0.75) and Item 11 (0.67), indicate that these items are very good at distinguishing students with critical thinking skills. Moreover, all items' Infit MNSQ and Outfit MNSQ values are within the acceptable range (0.5 to 1.5).

Measurement of CT Subscale on the Topic of Photosynthesis

The measurement results on each subscale of critical thinking skills showed significant differences in the difficulty level between essential sub-skills of thinking (Table 4). Inference is the most difficult sub-skill for students, while evaluation is the easiest. These differences reflect variations in students' ability to use different aspects of critical thinking skills and indicate that the instrument accurately measures various levels of these skills.

Table 4
Measurement Results on CT Aspects of Photosynthesis Topic

Subscales	Correct answer (%)	Item Difficulty (logit)	Standard error (logit)	Infit MNSQ (logit)	Outfit MNSQ (logit)	Point measure corr (logit)
Inference	11.82	1.17	0.10	1.04	1.10	0.50
Assumption	36.46	-0.61	0.11	1.06	1.06	0.53
Deduction	22.46	-0.58	0.11	0.98	0.97	0.53
Interpretation	21.60	-0.21	0.10	0.91	0.87	0.64
Evaluation	73.66	-0.65	0.11	1.06	1.13	0.51

Inference had the highest difficulty level with an item difficulty value of 1.17 logits, which means that this sub-skill was the most difficult for students, as shown by the lowest percentage of correct answers, 11.82%. The high difficulty indicates that students had difficulty concluding the information presented. Nonetheless, the Infit MNSQ (1.04) and Outfit MNSQ (1.10) values are still within acceptable limits, indicating that the item fits the model despite the slight variation in students' answer patterns. Assumption had a lower difficulty level (-0.61 logit) and a higher percentage of correct answers (36.46%). The Infit MNSQ and Outfit MNSQ values were 1.06 each, indicating that the items in this sub-skill performed well and fit the Rasch model. Deduction also had a low difficulty level (-0.58 logit) and a correct answer percentage of 22.46%. It is similar to the assumption in terms of difficulty, and the Infit MNSQ (0.98) and Outfit MNSQ (0.97) values indicate that the items in this sub-skill fit the model well and are consistent in measuring students' skills. Interpretation had a lower difficulty level than Inference, with an item difficulty of -0.21 logit and a percentage of correct answers of 21.60%. It displays good ability in interpreting information, as reflected by the Infit MNSQ (0.91) and Outfit MNSQ (0.87) values, which are in the excellent range, indicating high consistency in measurement. Evaluation is the easiest sub-skill with an item difficulty of -0.65 logit and the highest percentage of correct answers (73.66%). However, despite being more accessible, this item had a slightly higher Outfit MNSQ value (1.13), indicating variation in student answer patterns, although the Infit MNSQ value (1.06) was within acceptable limits.

Discussion

Instrument Reliability and Validity

The analysis of reliability coefficients at the person (0.86) and item (0.95) levels yielded high values, indicating that the instrument performs consistently. The high item reliability (0.95) suggests that the instrument can reliably identify the difficulty level of the items, while the person reliability (0.86) suggests that the instrument is consistently effective in measuring individual ability across repeated assessments. According to classical reliability theory, values above 0.80 are considered good, and values above 0.90 are highly reliable (Lord, 1980), indicating that this instrument is highly reliable for assessing critical thinking skills in the context of photosynthesis. Although

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the person reliability of 0.86 is satisfactory, further improvements in consistency may be achieved through strategies such as revising ambiguous items or adding questions that are more appropriate for the target population (Hambleton et al., 1991). Enhancing person reliability involves refining the instrument to better align with the studied population, ensuring it accurately reflects the respondents' abilities in the photosynthesis-based critical thinking task (Baker & Kim, 2017).

The analysis also examined the Infit and Outfit MNSQ values to assess the fit of the data to the Rasch model. A mean close to 1 for Infit and Outfit MNSQ indicates a good fit, meaning the instrument fits the Rasch model (Laliyo et al., 2022). However, extreme values were detected in Outfit MNSQ, such as 4.32 for a particular respondent, which is well above the ideal range (Linacre, 2011). Optimal Infit and Outfit MNSQ values generally fall between 0.5 and 1.5, representing responses that fit the Rasch model predictions (Adams et al., 2019). High Outfit MNSQ values indicate the presence of outliers, possibly due to randomness or lack of involvement in the response. While these extreme values may be considered anomalies, they may provide insight into individual differences, such as unique response patterns or respondent-specific behaviors (Field, 2024). The outliers should not be removed automatically; they require further analysis to understand why these values occur (Nielsen et al., 2017). This analysis helps refine the measurement process and increase its validity.

The range of person measures (-2.60 to 2.65) indicates significant differences in respondents' abilities, while the range of item measures (-0.86 to 1.26) indicates moderate variation in item difficulty. The relatively wide range of person measures suggests that the instrument captures a broad spectrum of abilities in the context of critical thinking in photosynthesis, while the moderate range of item measures implies that the items are varied enough to assess these skills across different ability levels effectively (Huelmann et al., 2020). The broader range of this direct measure reflects the instrument's ability to identify variations in respondents' critical thinking skills in biology (Bond, 2015). The choice of photosynthesis as the context for assessing critical thinking skills is unique, as this specific application in biology has not been explored in other studies. Focusing on photosynthesis-related critical thinking provides a new perspective in evaluating critical thinking in the discipline (Linacre, 2011 and Wang & Ho, 2024).

Item Difficulty and Discrimination

The analysis of item difficulty and discrimination in this study revealed several specific findings, some of which differ from previous research and contribute unique insights. Item difficulty ranged from -0.86 (easiest item) to 1.36 (most difficult item), covering a broad enough spectrum to assess respondents of varying abilities. According to the Rasch model principle, a wide range of item difficulties is essential to capture the full spectrum of respondents' abilities (Cascella et al., 2020; Huelmann et al., 2020; Wind, 2019). Additionally, the percentage of correct answers provides insight into respondents' perceived difficulty, reinforcing the alignment between item difficulty measured by the Rasch model and respondents' actual perceptions. However, some respondents found certain items too easy or tricky, suggesting the potential for adjustments to better suit a more diverse population (Affandy et al., 2021; Laliyo et al., 2022).

A unique finding in this study was the presence of high Outfit MNSQ values, especially for Items 2 and 8, which showed values greater than 1.15. Although most items had Infit and Outfit values close to 1—indicating an overall good fit to the Rasch model—the items showed deviations of concern. While Outfit values in the range of 0.5 to 1.5 are generally acceptable for reliable measures of ability (Bond, 2015), the higher Outfit values observed here may indicate unanticipated respondent behavior or item-specific misfits that deviate from model expectations. These elevated values are a unique finding in this study and highlight potential areas for further research, distinguishing the current study by revealing variability not typically observed in similar assessments.

Point-measure correlation values also indicate item-specific differences in discrimination ability. For example, Item 10 has a high point-measure correlation of 0.75, which indicates a strong ability to discriminate between respondents of different abilities, whereas Item 1 has a lower correlation of 0.49, indicating a reduced ability to discriminate effectively. According to the literature, items with a correlation above 0.70 are considered strong indicators of discrimination between high- and low-ability respondents, while values below 0.50 suggest that the item may be less effective in this regard (Affandy et al., 2021; Laliyo et al., 2022; Linacre, 2011). A lower correlation for Item 1 does not necessarily indicate that the item should be removed, as the item may be highly relevant for certain subgroups of respondents (Bond, 2015). The current findings uniquely contribute to the literature by highlighting items that exhibit different levels of discrimination, emphasizing the need for items that can effectively separate ability levels across different respondents.

Furthermore, the current study found low standard errors for the item difficulty measures, ranging from 0.10

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to 0.12, indicating high accuracy. Low standard errors suggest minimal deviation from the estimated difficulty level, thereby increasing confidence in these measures (Cascella et al., 2020; Collado et al., 2015). However, it is also essential to consider that although low standard errors improve measurement accuracy, other potential sources of error, such as systematic bias, can still affect the instrument's validity (Cascella et al., 2020; Huelmann et al., 2020; Wind, 2019). The findings of low standard errors, combined with specific differences in Infit and Outfit values for certain items, offer a nuanced understanding of the instrument's performance (Bond, 2015; Linacre, 2011), marking a distinct contribution to the field of critical thinking assessment in biology education.

Variation of Critical Thinking Skills between Sub-Skills

The analysis of variation in critical thinking sub-skills in this study highlighted specific findings, some of which provided new insights that set it apart from previous studies. The inference sub-skill was the most challenging for the respondents, with a high difficulty level of 1.17 logits, indicating that the students had difficulty drawing conclusions from the given data or evidence. Meanwhile, the evaluation sub-skill, with a lower difficulty of -0.65 logits, was more accessible to the respondents. This discrepancy suggests that sub-skills with positive logits (e.g., inference) involve greater cognitive complexity, requiring higher analytical ability to arrive at the correct conclusion (Bond, 2015; Linacre, 2011). Previous research also indicates that inference is more cognitively demanding than evaluation (Anggraeni et al., 2023; Falloon et al., 2022; Teresa & Fields, 2023; Yeung et al., 2023). The difficulty observed in the current study suggests a unique challenge in the context of critical thinking in photosynthesis, highlighting the need for specialized teaching methods designed to improve students' inference skills in this area of study.

Another unique finding in this study was the slight deviation in Infit and Outfit values for certain sub-skills. Although most sub-skills had Infit and Outfit values close to 1, indicating an acceptable fit with the Rasch model (Linacre, 2011 and Wang & Ho, 2024), the inference sub-skill had an Infit value of 1.04 and an Outfit of 1.10, while the evaluation sub-skill had an Outfit value of 1.13. While these values are within the tolerance limits, they suggest that some respondents may not answer consistently for the inference or evaluation tasks, perhaps due to different levels of understanding or different approaches to answering (Baran et al., 2021; Clements & Joswick, 2018; Teresa & Fields, 2023). The variation in fit metrics for specific sub-skills is a distinct aspect of this study, contributing to a deeper understanding of how respondents interact with tasks of varying levels of complexity within a critical thinking framework in biology. These findings highlight the importance of further analysis and refinement of specific sub-skills, especially inference, to improve the instrument's accuracy in diverse respondent populations.

The bubble chart analysis found that some items, such as items 3 and 8, had Infit or Outfit values outside the normal range. These findings indicate a potential mismatch between respondents' answer patterns and model expectations for these items (Cascella et al., 2020; Collado et al., 2015). Previous research has indicated that items with significantly out-of-range values often require revision, potentially due to ambiguities in item content or mismatches with respondents' abilities (Affandy et al., 2021; Laliyo et al., 2022). However, an out-of-range score for a particular item in this study does not necessarily warrant removal of the item (Linacre, 2011); instead, it invites a closer look at possible respondent variation or alternative interpretations. These unique findings contribute to the literature by demonstrating that certain items in biology-related critical thinking tasks require careful analysis to ensure alignment with diverse respondent populations.

The findings of this study offer practical insights for teaching critical thinking skills in the classroom, especially in the context of photosynthesis. The high difficulty level of the inference sub-skill suggests that students may benefit from more structured and purposeful learning approaches that emphasize drawing conclusions from complex data. For example, inquiry-based approaches or problem-based learning (PBL) can help students improve their inference skills through exploration and problem-solving activities (Angell et al., 2004; Jia et al., 2017). Furthermore, scaffolding techniques can enhance students' evaluation and deduction abilities by guiding them through the logical steps to critically assess information (Gauvain, 2020; Honomichl & Chen, 2012). In the context of photosynthesis, students can be given tasks such as analyzing the experimental setup or critiquing arguments about the factors that influence the process, providing a hands-on approach that encourages a deeper understanding and supports the development of critical thinking skills. These recommendations, rooted in the specific findings of the current study, highlight the need for educational strategies tailored to the complexity of each critical thinking sub-skill, particularly in biology.

The results of this study provide implications for educational policies and teaching strategies, particularly in areas rarely highlighted in previous research. This research offers new insights for teachers to design inquiry-based or problem-based learning approaches, especially in photosynthesis in biology, to help students improve critical

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thinking sub-skills such as inference and evaluation. The different difficulty levels identified in these sub-skills suggest that teachers can use targeted learning activities that challenge students' analytical abilities. For example, designing inquiry tasks that guide students to conclude complex photosynthesis-related data can fulfill the higher cognitive demands associated with inference. For educational policymakers, these findings underscore the importance of curriculum development beyond traditional content mastery to explicitly include critical thinking components in science courses, ensuring that all scientific material—such as biology topics like photosynthesis—integrates critical thinking elements. Furthermore, the results of this study support the inclusion of critical thinking tasks in a structured manner within each topic to systematically develop these skills. Moreover, the results of this study could support policy decisions to increase time allocation for PBL and inquiry-based learning in the science curriculum, as these methods show potential to promote critical thinking across diverse student abilities.

Limitations and Directions for Future Research

According to the findings, some essential suggestions for future research focus on exploring critical thinking skills in science or other subjects. Future research could deepen the understanding of how each sub-skill develops across different educational contexts and subjects. Further research could also examine the effectiveness of various learning approaches, such as inquiry-based learning, problem-based learning, and project-based learning, in supporting the development of critical thinking skills, both in general and specific to certain sub-skills. Moreover, path analysis or Structural Equation Modeling (SEM) techniques can examine the causal relationship between critical thinking sub-skills and other factors, such as learning motivation, attitude toward science, or learning strategies. The Latent Class Analysis (LCA) or Latent Profile Analysis (LPA) approach can help identify groups of students based on critical thinking profiles, which makes it possible to see patterns of individual differences in the mastery of certain sub-skills.

Conclusions and Implications

The study explored the critical thinking skills of lower-secondary school students on photosynthesis material, using an instrument based on the Watson-Glaser Critical Thinking Appraisal and analyzed with the Rasch Model approach. Findings revealed that students struggled the most with inference, while evaluation was the easiest subscale for them to master. The study's implications suggest that the Rasch Model offers a more objective and detailed approach for evaluating critical thinking skills, which can inform the development of targeted teaching strategies. This research can aid educators and policymakers in identifying students' strengths and weaknesses, allowing for more effective interventions in science education. For future research, it is recommended to apply similar instruments to other science topics to further validate the use of the Rasch Model in evaluating critical thinking skills across different contexts.

Declaration of Interest

The authors declare no competing interest.

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